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BEAM POSITION MONITOR USING A SINGLE CAVITY

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Abstract

Beam tests have been carried out with a cylindrical cavity tuned to 2.415 GHz which is the third harmonic of the accelerator frequency. The beam excites a TM_{110}-like mode when the centroid is displaced horizontally and an orthogonal mode when the beam is displaced vertically. The phase reversal detected when the beam crosses the plane of symmetry identifies the cartesian quadrant occupied by the beam. The signals are proportional to beam current and displacement with average slope $0.35\ mW^{1/2}\cdot mm^{-1}\cdot mA^{-1}$.

Introduction

High power beams of charged particles demand beam monitors which are non-intercepting and microwave monitors are of this type. The underlying principle of the monitor to be described has been used for accurate determination of the beam position at the Stanford Linear Accelerator Center (SLAC) for many years[1]. In the SLAC beam monitors, fields from the beam bunches excite a passive rectangular cavity in the TM_{120}-mode and from the amplitude of the mode the transverse position of the beam centroid in one dimension is determined, provided the beam current is known. A second adjacent cavity rotated through 90° locates the beam centroid in the perpendicular direction about $\lambda/2$ downstream. The complete system is sensitive to beam displacements of a few microns. The Mainz group propose to use a similar system of rectangular cavities in the cw microtron presently under construction[2].

In the experiments to be described the beam couples to the longitudinal electric fields of two TM_{110} modes of a cylindrical cavity. The bimodal cavity is constructed in such a way that the symmetry axes of the two modes (in the plane perpendicular to the beam) are at right angles. Adjustments consistent with the symmetry are next carried out to make the frequencies of the two modes equal; the two modes can then be excited simultaneously when the beam is displaced transversely. However, there exist two mutually perpendicular directions of displacement for which only one mode is excited. Thus measurement of the excitation of the two modes gives the magnitude of the components of displacement in the two special directions.

Cavity Description

In the TM_{110}-mode the electric field is zero on axis and its direction changes sign across the plane of symmetry. The magnetic field is maximum on axis and has reversal points defined by the polar co-ordinates $r = 0.481\ a$, $\phi = 0$ and π which represent regions of maximum electric field with equal and opposite longitudinal vectors. When the beam current is known the amplitude of the cavity oscillations can be interpreted to give the displacement from the plane of symmetry while the phase gives the sign of the displacement.

In practice, any departure from azimuthal symmetry represents a perturbation to the cavity fields causing modes to split into components having similar field patterns but different resonant frequencies.

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Chu[3] has shown that when a circular cavity is made elliptical, modes with azimuthal asymmetry in their field distributions will break up into two orthogonal component modes with different resonant frequencies.

A cavity has been constructed in which quadrupolar symmetry is created by introducing tuning plungers at radial positions near the electric field maximum. This symmetry has been maintained by four magnetic coupling loops on the circumference. TM_{110}-like modes, perpendicular to one another can be excited from a hole situated at the centre. Figure 1 is a sketch showing the principles involved. A similar type cavity was built by Sorokin[4] for use in paramagnetic studies.

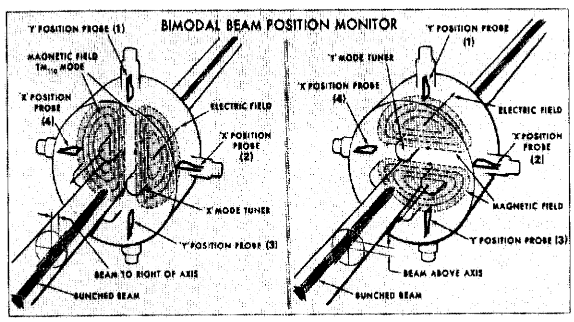

Fig. 1 Bimodal Beam Position Monitor

Using Slater's[5] criteria it is possible to tune the modes to the same frequency by moving the two symmetrically arranged pairs of tuning screws. The tuners are small copper discs located by beryllium/copper fingers inside a 1.25 cm hole. Movement of the tuners is possible through stainless steel bellows. The four symmetrically placed magnetic probes on the outer circumference are located so that magnetic lines of force belonging to one mode only, can thread through one pair of probes.

The cavity is designed to work at 2415 MHz which is the third harmonic of the accelerator frequency. The bunched beam passes through a 3.8 cm diameter hole in a cavity which internally is 14.75 cm in diameter and 6 cm long. The charged particle beam excites the modes appropriate to its cartesian co-ordinates. In the general case both modes will be excited simultaneously whereupon the amplitude of each signal is used to determine the magnitude of the co-ordinates and the phases must be determined to obtain the signs of the displacements.

Bench tests were carried out on a prototype bimodal cavity designed to operate at 805 MHz. The common oscillator was used to excite both modes simultaneously through probes[6] (1) and (2) of Fig. 1. Experiments showed that the relative phase and amplitude of the modes could be varied independently and the isolation was greater than 40 dB.

Beam-Cavity Interaction Theory

Using a similar approach to that found in Ref. 1 it is possible to determine the sensitivity of the beam sensor provided all beam characteristics are known. In our experiments the longitudinal phase distribution can only be estimated from beam dynamics calculations but the derivation of the rf power output for a given beam deflection serves to act as a guide to optimize the design parameters.

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The longitudinal electric field E and the beam current I are both functions of space and time and the power is defined by

$$P = \int_{-\infty}^{\infty} E(z,t) \times I(z,t)\, dz. \tag{1}$$

The time average value of interest of this product is

$$P_b = 1/2 \int_{-\infty}^{\infty} E_z(z) \times I_3^* \, dz \tag{2}$$

where I_3^* is the peak value of the third harmonic component of the beam current. For our cavity E_z and I_3 are in phase and if we assume a $\cos^2$ longitudinal charge density distribution then I_3 is twice the average beam current, I, during the micropulse. Hence

$$P_b = I \int_{-\infty}^{\infty} E_z \, dz. \tag{3}$$

For simplicity if we assume that the cavity walls do not have a beam hole then when the beam is displaced to a point (r',o) the longitudinal electric field is

$$E_z = E_I(r',o)\; J_1(k_c r)\cos\phi \tag{4}$$

in a cylindrical co-ordinate system where k_c is the propagation constant $2\pi/\lambda$. $J_1(k_c r)_{max} E_I(r',o)$ is the maximum electric field for this beam position when the TM_{110} mode is excited. The power delivered to the cavity can also be expressed in terms of the loaded shunt resistance, R, hence

$$P_b = \frac{[\int E_z(dz)]^2}{2R} = \frac{h^2}{2R} E_I^{\,2}(r',o)\; J_1^{\,2}(k_c r)\cos^2\phi. \tag{5}$$

Independently the quality factor, Q, can be determined from the defining relationship between the stored energy, U, and the average power loss per cycle P_b namely

$$Q = \frac{2\pi f\, U}{P_b}. \tag{6}$$

Combining equations (5) and (6) gives

$$\frac{R}{Q} = \frac{h^2\, E_I^{\,2}(r',o)\; J_1^{\,2}(k_c r)\cos^2\phi}{4\pi f\, U}. \tag{7}$$

For any cavity the stored energy in either the electric or magnetic field is a maximum when the other is zero. Hence

$$(U_E)_{max} = \frac{\varepsilon}{2} \iiint_V |E|^2\, dv. \tag{8}$$

For the TM_{110}-mode the total stored energy in a cavity of radius a and length h is then

$$U = \frac{\varepsilon}{2 \times 0.399} \int_0^a \int_0^{2\pi} \int_0^h E_I{}^2(r',o)\; J_1^{\,2}(k_c r) \times \cos^2\phi \; rdz\, d\phi\, dr \tag{9}$$

$$= \frac{\varepsilon}{0.339} \cdot \frac{\pi}{4} \cdot E_I^{\,2}(r',o)\; a^2 h\; J_o^{\,2}(k_c a) \tag{10}$$

The boundary condition that the electric field is zero at the cavity wall requires that $J_1(k_c a)=0$ where a is the cavity radius, hence the first root occurs at $k_c a$ = 3.83. The corresponding value of -0.41 for the function $J_o(k_c a)$ gives

$$U = 0.39\; \varepsilon\; E_I^{\,2}(r',o)\; a^2 h. \tag{11}$$

and, from equation (7),

$$R = \frac{Q\, h\, J_1^{\,2}(k_c r)\, \cos^2\phi}{4\pi \times 0.39\, \varepsilon\, f\, a^2}. \tag{12}$$

The power given up by the beam, P_b, will be shared between losses in the cavity wall, P_c and the signal sent out to the detector, P_o. Hence if $K = P_o/P_c$ then $P_o = P_b\, K/1{+}K$. Substituting equation (5) into equation (3) gives

$$P_b = 2RI^2 \tag{13}$$

and when combined with equation (12) and multiplied by the coefficients for bunch length, $B_\ell = \sin(\pi\ell/\beta\lambda)/(\pi\ell/\beta\lambda)$ and transit time, $T = \sin(2\pi h/\beta\lambda)/(2\pi h/\beta\lambda)$ we have

$$P_o = 1.28\, \frac{Q_L}{\varepsilon f} \cdot \frac{h}{\pi a^2} \cdot \frac{K}{(K+1)} \cdot J_1^{\,2}(k_c r)\, \cos^2\phi \cdot I^2 \cdot B_\ell \cdot T \tag{14}$$

Calculations using a beam dynamics computer code indicated that our beam has a half width in longitudinal phase space of 15° hence there is little loss of sensitivity in working at the third harmonic.

Beam Tests

Beam tests were carried out with a cavity machined out of a solid block of OFHC copper. The magnetic probes were fixed and the vacuum feed-through connectors were supported on small steel vacuum flanges. Stainless steel tubes were brazed into the beam holes and steel vacuum flanges were welded to mate with the beam line of the Electron Test Accelerator (ETA)[7]. A photograph of the cavity is shown in Fig. 2.

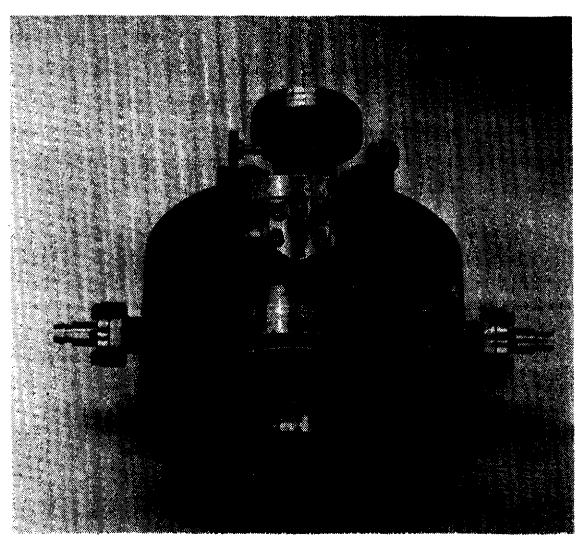

Fig. 2 Photograph of Monitor used in Beam Tests

Experiments were carried out to verify the underlying concept of using a bimodal cavity as a beam position monitor, to verify the general theory and establish calibrations. The beam used was the cw, 1.5 MeV electron beam from the first accelerating structure of ETA. The mechanical system used is shown schematically in Fig. 3. Stable conditions were maintained in the accelerator while the cavity was moved horizontally and vertically. The rf signals were sent to the control room about 15 m away. Standard diode detectors were used and the voltage signals were converted to power readings using least squares polynomial fits. Prior calibrations of cable signal loss were allowed for.

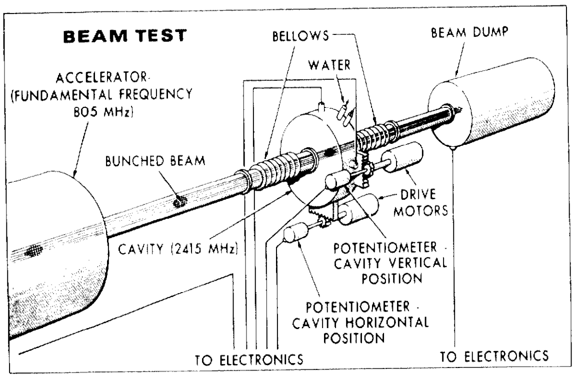

Fig. 3 Sketch of Equipment for Beam Tests

The first experiment was to move the cavity horizontally with the beam held steady at about 1 mA. Figure 4 shows the power level from the right probe and the beam displacement during the run. The signal drops to zero as the beam passes through the horizontal plane and then increases again. A change in phase of π radians was observed at the null.

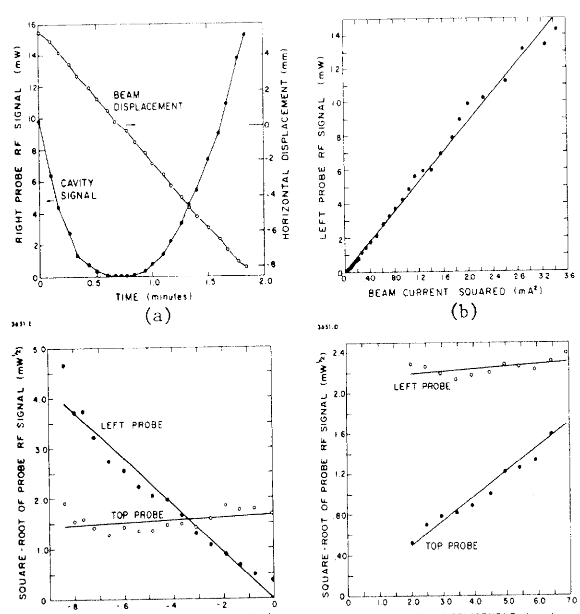

Fig. 4 Results of Beam Tests

Variation of power output with beam current was measured with the beam off centre. The result shown in Fig. 4(b) confirms the theoretical prediction that when the cavity and beam positions are fixed, power extracted from the beam is proportional to I^2. Further confirmation of the theory is seen in Figs. 4(c) and (d) where the beam-normalized power output is proportional to the square of the displacement with a horizontal displacement sensitivity of 0.46 $mW^{1/2}\cdot mm^{-1}\cdot mA^{-1}$. This data was taken in a test of mode isolation for the general case when the beam is placed deliberately to excite both modes simultaneously. Both figures show that when the cavity is moved horizontally or vertically only the appropriate signal changes. The theoretical prediction that the constant product $J_1(k_c r)\cos\phi$ will introduce a variation of about 4% for the conditions of Figs. 4(c) and (d) was not tested in these first experiments.

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